Vegetation Microchannels Effect on Overland Flow Velocity

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VEGETATION MICROCHANNELS EFFECT ON OVERLAND FLOW VELOCITY

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By

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Abstract

Determining overland water flow characteristics, specifically velocity, is an important factor in understanding the production and transport of sediment, nutrients and pollutants by runoff water. Current runoff models express overland flow as a uniform, thin "sheet" of water. This simplification overlooks the inherent variability of flow depths and velocities in concentrated flow paths among and through the vegetation elements. A series of laboratory flume studies evaluated the role of the grass stems and flow paths on the Manning's n roughness coefficient. Water flow velocities in 2 lawn grasses, Kentucky bluegrass (*Poa pratensis*) and common fescue (*Festuca rubra*), and 2 shortgrass prairie range grasses, blue grama (*Bouteloua gracilis*) and inland salt grass (*Distichlis spicata*), were determined using the continuity equation and a dye tracer. Mean flow velocities through the 2 lawn grasses were similar at all 3 flow rates. Velocities increased from 0.5 cm sec^{-1} to approximately 1.0 cm sec^{-1} as the channel slope increased from 3.4 to 7.0%. When channels were cut into the grasses, the mean flow velocity increased almost an order of magnitude and the dye velocities were 2 to 3 times greater than when there were no channels. On the native grass, the dye velocities were slower than the computed mean velocities. Dye velocities ranged from less than 3 to almost 5 cm sec^{-1} . The Manning's n computed using these measured flow velocities were 2 times to an order of magnitude greater than previously reported. These values are believed to be more realistic and representative for determining overland flow velocities through vegetation and microchannels around vegetation.

Introduction

Overland water flow is a significant factor in the production and transport of sediment, nutrients and pollutants. The flowing water erodes the soil and carries the detached soil particles downslope and potentially contaminate ponds, streams and rivers. Grass buffers and vegetative filter strips are commonly used to slow the water velocity and trap the sediment, nutrients and pollutants in runoff water from agricultural lands before they reach the rivers or ponds (Dillaha et al. 1989, Robinson et al. 1996). The vegetation increases drag resistance of shallow overland flow which reduces the water velocity allowing the carried sediments to be dropped from the flowing water.

Current runoff models express overland flow as a uniform, thin “sheet” of water (Abrahams et al. 1986). This simplification overlooks the inherent variability of flow depths and velocities in concentrated flow paths among and through the vegetation elements. In most instances, native vegetation is not a solid, dense matting but instead consists of irregularity spaced vegetation clumps. The vegetation clumps are usually located on a slightly higher surface topography than the “interspaces” with water flow paths, “microchannels”, around the edges. Many natural pasture and rangeland upland areas are characterized by this type of vegetation. These microchannels are typically 2-8 cm wide and the flow depths from rainfall runoff may not exceed 1-2 cm. The water flow through the microchannels around the clumps is a more open channel type as opposed to a non-submerged flow through the vegetation. In some instances there is vegetation which crosses the flow paths causing a discontinuity of the microchannel down the slope. Estimating water flow velocity for these conditions is not an easy task. The flow is a combination of both open channel (micochannel) and flow through non-submerged vegetation.

Most models of water flow velocity were developed in open channels where the roughness of the conveyance channel was the main drag component. One common method of characterizing flow velocities in open channels is the use of Manning's formula (Chow 1959). In Manning's equation, the channel roughness is characterized by an empirical coefficient, n. The values of the coefficient, n, have been determined for many different surfaces. In most large open channels the value of n does not change with changes in the flow depth. The surface roughness height affecting the drag resistance is small compared to the depth of flow.

In flow where there is submerged vegetation in the channel, there is an additional resistance imparted to the flow by the vegetation in addition to the roughness of the channel bottom and sides. Under these conditions Petryk and Bosmajian (1975) found the Manning's n to be a function of not only the flow depth but also the submerged vegetation stem density.

In shallow flow through vegetation (non-submerged) the resistance to the flow is even less understood. The vegetation stem density and spacing become an even more important component of the total flow resistance. Jin et al. (2000), in a laboratory study using cylindrical polypropylene bristles to simulate vegetative filter strips, found that the flow velocity in non-submerged vegetation can be described by the Manning's formula with a varying roughness coefficient. The coefficient had 2 components. One component represents the bed shear stress and is characterized by the conventional Manning's n. The other component represents the drag force from the vegetation and is proportional to the vegetation density and flow depth.

We conducted a laboratory flume study to evaluate the effect of microchannels on water flow velocities in 2 types of lawn sod vegetation. From these velocity measurements, we calculated a Manning's n for both a solid grass matting and for small microchannels cut into the grass. These results are compared to measured flow velocities across the surface of undisturbed

vegetated soil monoliths taken from 2 shortgrass rangeland prairie sites and field measurements of water flow velocities down a shortgrass prairie hillslope.

Methods and Materials

Analytical Considerations

Mean flow velocities across the vegetation mats can be computed using the continuity equation:

$$V=Q/A \qquad \text{................(1)}$$

where,

V = the water velocity,

Q = the measured flow rate,

A = the cross sectional area of the flow (H x w), assuming a rectangular channel

and,

H = flow depth

w = flow width.

If the flow is in an open channel, this computed velocity (V) inserted into the Manning's equation (Chow 1959),

$$V = (1.0/n)\, R^{2/3}\, S^{1/2} \qquad \text{..........(2)}$$

where,

R = the hydraulic radius of the of the channel

= cross sectional flow area (A) divided by the wetted perimeter (P)

P = 2H+w

S= the slope of the channel,

can be used to estimate a channel roughness parameter, n (Manning's n)

For shallow flow in a rectangular channel the depth of flow is minor compared to the width and the hydraulic radius becomes the cross sectional area (w x H) divided by width (w) or simply

R = the depth of water flow (H). ....(3)

Combining equations 2 and 3 gives an estimate of Manning's n roughness coefficient as function of flow depth only.

$$n = (1.0/V)\, H^{2/3}\, S^{1/2} \qquad \text{.................(4)}$$

As discussed earlier, when the flow is passing through non-submerged vegetation, the roughness coefficient, n, can be represented as the sum of 2 components; a boundary roughness coefficient and a vegetative drag force coefficient (Jin et al. 2000). Petryk and Bosmajian (1975) describe this combined roughness coefficient as:

$$n = \left(n_o^{2} + (C_d/2g)DH^{4/3}\right)^{1/2} \qquad \text{.........................(5)}$$

where,

n_o = roughness coefficient excluding the effect of vegetation

C_d = drag coefficient of the vegetative elements (assumed equal to 1, (Jin et al.2000))

D = product of stem diameter (w_s) and stem density (N) (Jin et al. 2000).

If there is no vegetation, Equation 5 reduces to:

$$n = n_o \qquad \text{...................(6)}$$

where n is the roughness coefficient (Manning's n) for overland flow over a bare surface.

Experimental Procedures

A tilting laboratory flume, 6.1 m. long with a channel of 46 cm wide and 15 cm deep was used to evaluate flow velocities in vegetation. A test section 1 m. long, midway down the flume, was installed with a false floor in the shape of a trapezoid, 22 cm center base and 3.8 cm side slope height. A plywood bulkhead with an opening in the shape of a rectangle with a width of 4 cm located 2 cm above the flume floor was at the upper end of the test section.

Two lawn grass sod mattings from a sod replacement farm and 2 undisturbed soil monoliths from native shortgrass rangeland prairie sites were used in the studies. The grass mattings sod rolls, 60 cm wide and 100 cm long, of Kentucky bluegrass (*Poa pratensis*) and common fescue (*Festuca rubra*), approximately 2 cm thick base with stems approximately 6 cm long, were obtained from a sod farm near Fort Collins, Colorado. The native grasses were undisturbed sod, 8 cm thick, 60 cm wide and 100 cm long, cut from 2 range sites at the Central Plains Experimental Range (CPER) 60 km northeast of Fort Collins, Colorado. One was predominately blue grama (*Bouteloua gracilis*) and the other inland salt grass (*Distichlis spicata*).

The grass mattings (bluegrass and fescue) were placed in the test section with the base of the grass stems at the same elevation as the bottom of the rectangular opening in the bulkhead. The native grass cut sod (blue grama and inland salt grass) monoliths were placed in the test section with the soil surface at the same elevation as the bottom of the rectangular opening in the bulkheads (Fig. 1).

Two flume slopes were used, 3.4 and 7.0%. The actual slope of the grass matting or soil monolith was determined by placing a straight edge on the grass/soil surface and measuring the slope.

Water was introduced at a constant rate into the upper end of the flume. A pool of water would form above the first bulkhead and flow through the opening in the bulkhead onto the grass mat. The rate of water flow was volumetrically measured for timed intervals at the flume outlet. Three rates of water flow (20, 30, and 60 cm^3 sec^{-1}) were evaluated for each grass. Four to 9 separate mats of each grass were evaluated for each water flow rate and flume slope. Two to 6 separate soil monoliths of each grass from CPER were evaluated at flow rates of 20 and 30 cm^3 sec^{-1} for each flume slope.

Mean flow velocities based on the continuity equation (Eq. 1) were computed. For the grass mattings, the cross-sectional area (A) was based on the measured water depth (H) and assuming the flow cross-section was a trapezoid shape similar to the shape of the flume floor (Fig. 2 top). For the soil monoliths the depth and width of the flow in the natural microchannels were measured at 4 to 8 locations down the length of the test section.

Peak flow velocities were measured using a water soluble red organic dye. Approximately 1 ml of dye was placed on the water surface at the upper end of the test section. The rate of the advancing front of the dye was timed through an 80 cm long length in the test section.

On the grass sod mattings, the velocity was measured 3 times through the grass at each flow rate. A microchannel, 4 cm wide, was then cut in a meandering path through the grass with small grass clippers (Figs. 3, 4). The mean and dye flow velocities were again measured 3 times for each flow rate (Fig. 5). For each run the depth of water flow at 4 locations were measured within the test section. At each of these locations the width of the water flow or the width of the cut microchannel in the vegetation was measured.

On the native grass monoliths the water was allowed to flow through the natural microchannels. No effort was made to create flow paths.

The vegetation density of each grass was determined in a 6.8 cm diameter ring at 4 random locations. The stem size was measured on 10 grass stems collected from the cut microchannels and measured with a micrometer at the base of the cut. One measurement was made if the stems were round. On oval shaped stems the width was measured for both axis.

Results and Discussion

Flow Velocities—Lawn Grass Matting

There were differences in both the stem density and stem diameter between the 2 grasses. Stem densities were 3.2 and 2.3 stems cm^{-2} for the fescue and blue grass respectively. The fescue grass blades were circular with a diameter of 1.5 mm, while the blue grass blades were oval shaped with dimensions of 1.8 x 0.9 mm.

Mean flow velocities through the grasses with no channel were similar for the 2 grasses for all 3 flow rates. Velocities increased from 0.5 cm sec^{-1} to approximately 1.0 cm sec^{-1} as the channel slope increased from 3.4 to 7.0%. There was essentially no effect of the water flow rate on the measured water velocities (Fig. 6a). Flow velocities as measured with the dye decreased from 2 cm sec^{-1} at the high flow rate to less than less than 1 cm sec^{-1} at the low flow rate. The channel slope had minimal effect on the dye velocities through the vegetation (Fig.6b).

When channels were cut into the grasses, the mean flow velocity increased almost an order of magnitude and the dye velocities were 2 to 3 times greater than when there were no channels (Figs. 6c, 6d). There was a decrease in both the mean and dye flow velocities in the channels with decreasing flow rates (Fig. 6c, 6d).

Flow Velocities—Undisturbed Soil Monoliths from CPER

Determining the mass flow velocities across the undisturbed soil monoliths from the range sites on the Central Plains Experimental Range was not as straight forward as the studies with the grass mattings from the sod replacement farm. The blue grama and salt grass from the field sites tend to grow in irregular shaped clumps with bare areas between and around the clumps. The water would flow down the bare areas in varying widths and depths. Frequently the bare areas would have a narrow vegetative strip growing across the lower edge of the area. This would cause the water to form a small pool. Water would pass slowly through the grass barrier into the next bare area or pool. This type of flow can be characterized as "cascading pools." This flow characteristic can be seen in the dye paths in the series of 4 photos in Figure 7.

The varying widths of the flow paths made it difficult to compute the mean flow velocity using Equation 1. A mean cross sectional area was calculated from the width and depth measurements made down the flow path. Computed mean velocities varied from 4 to 5 cm sec^{-1} at the lower flume slope (3.4%) to over 11 cm sec^{-1} with the greater flume slope (7.0%) (Table 1). The irregular thickness of the soil monoliths made it difficult to obtain the designated slope of the soil surface (Table 1).

Contrary to the grass matting studies, the dye velocities on the undisturbed grass were slower than the computed mean velocities. Dye velocities ranged from less than 3 to almost 5 cm sec^{-1} . This reversal in relative velocities may be a result of several confounding factors. Some possible reasons are:

1. The "computed" mean cross-sectional area of the flow path may not be a good representation of the "effective" cross-sectional area that is controlling the flow.

2. There is no "average" flow velocity through the cascading pools. It was observed that the pools tended to fill with water until sufficient "head" developed to force the water through the vegetation into another pool at a lower elevation. There were instances where the water would then drain from the pool at a faster rate than it was being filled. A point would be reached where the "head" could not maintain the rate and the flow would temporarily slow down. The water would then have to re-fill the pool before flow would pass out the lower end and the process would start over. This phenomena would be occurring down the entire slope and resulted in the water flowing as a series of pulses.

Roughness Coefficient (Mannings n) – Lawn Grass Mattings

Accurate prediction of runoff flow velocities using Manning's equation (Eq. 2) is highly dependent upon the selection of the proper roughness drag coefficient, n. There is very little experimental data of the value of n for water flowing across a vegetative surface or through standing vegetation. Chow (1959) lists values on 0.03 to 0.05 for n. Flanagan et al. (1995) suggests n values of 0.20 to 0.30 for dense grass higher than the flow depth. Several studies have used cylindrical plastic bristles to simulate grass stems. Jin et al. (2000) using polypropylene bristles, reported Manning's n values of 0.005 to 0.15 depending upon the density of the bristles. Munoz-Carpena et al (1992) used the value of 0.012 (Manning's n for a cylindrical media).

In our studies the computed n values as defined by Equation 4 for water flowing over a grass mat through a cut channel ranged from 0.2 to over 1.7 (Fig. 8a). There were significant increases in the value of n as the flow rate decreased (flow depth decreased). In the studies with no cut channels, Manning's n ranged from 0.6 to 1.7, which was usually greater than when there

was a channel (Fig. 8b). It had been anticipated that the vegetative stems would be a major component of the drag force through vegetation. Using the vegetative drag coefficient component of Equation 5, $[(C_d/2g)DH^{4/3}]$, we estimated that the resistance of the stems added 0.05 to 0.14 to the Manning's n coefficient. These results indicate the major drag component was the base of the stems. This base resistance is believed to be the major factor in the drag coefficient in the cut channel data (Fig 8a). The short stubble remaining from the clipping provided a very effective drag force on the flowing water.

Roughness Coefficient (Mannings n) – Undisturbed Soil Monoliths (CPER)

By knowing the water velocity across a surface, a roughness coefficient (Manning's n) can be estimated using Equation 4. Applying the equation to the flume determined velocities for the soil monoliths from CPER shows Manning's n values of 0.06 to 0.9 (Table 1). These values are nearly an order of magnitude greater than previously reported for bare soil surfaces (Jin et al. 2000, Chow 1959) and even greater than suggested by Flanagan et al. (1995). The values are less than were obtained with the grass mattings (Fig. 8). The differences in the results between the lawn sod and field sod mats are attributed to the fact that the vegetation density on the CPER soil is not a solid covering, but rather in clumps with flow paths on bare soil around the grass (Fig. 7). The grass was not as dominating in controlling the water velocity. The grass did cause minor "dams" but did not restrict the flow to the extent of a solid lawn grass covering.

Field Explorations

A series of field investigations or water flow velocities over a blue gram grass dominated range site was conducted at the Central Plains Experimental Range (CPER). Water was applied

to the soil surface by spraying onto a sheet metal tray and allowing the water to flow off the lower edge (Fig 9 top). Downslope of the water placement, a green organic dye tracer was applied as a line source to the water flowing over the soil surface (Fig 9 middle). Further downslope the velocity of the water advancing front and the dye tracer was measured over a selected 1 meter interval (Fig 9 bottom).

The water flow patterns were similar to the cascading pools characteristic that had been observed in the laboratory studies. (Fig 7, 9 bottom). Measured flow velocities ranged from 0.3 to 1.7 cm sec^{-1} for the advancing front over dry soil. Dye velocities were 1 to almost 5 cm sec^{-1} (Table 2). These values were similar to the measured flow velocities over the CPER soil monoliths n the laboratory. On wet soil the advancing front velocities were 0.5 to 1.8 cm sec^{-1} with dye velocities of 1 to 5 cm sec^{-1}. Flow depths varied but were generally less than 1 cm deep.

Assuming a flow depth of 1 cm and using Equation 4, computed Manning's n in the field studies was 0.7 to 3.6 for the advancing front on dry soil and 0.28 to 0.93 for the dye (Table 2). There was a slight decrease in Manning's n values over the wet soil. The larger values for the advancing front over the dry soil is attributed to the slowness of the water to wet the soil and surface covering (grass, litter). Once water covered the soil surface, flow paths of higher velocities would develop following the path of least resistance. The dye tended to flow thes paths of least resistance. It was observed during dye measurement in both the field and laboratory studies that small "vortex" flow channels would develop which the traveled at a rate faster than the mainstream flow (Fig 5). It appeared that these vortex jets were caused by transverse flow vectors as the flowing water rounded a curve. The vortex jets when colored with dye could actually be seen passing through relatively still pools of water.

Summary and Conclusions

Determining overland water flow characteristics, specifically velocity, is an important factor in understanding the production and transport of sediment, nutrients and pollutants by runoff water. Current runoff models express overland flow as a uniform, thin "sheet" of water. This simplification overlooks the inherent variability of flow depths and velocities in concentrated flow paths among and through the vegetation elements. A series of laboratory flume studies evaluated the role of the grass stems and flow paths on the Manning's n roughness coefficient. Water flow velocities in 2 lawn grasses, Kentucky bluegrass (*Poa pratensis*) and common fescue (*Festuca rubra*), and 2 shortgrass prairie range grasses, blue grama (*Bouteloua gracilis*) and inland salt grass (*Distichlis spicata*), were determined using the continuity equation and a dye tracer. Mean flow velocities through the 2 lawn grasses were similar at all 3 flow rates. Velocities increased from 0.5 cm sec^{-1} to approximately 1.0 cm sec^{-1} as the channel slope increased from 3.4 to 7.0%. When channels were cut into the grasses, the mean flow velocity increased almost an order of magnitude and the dye velocities were 2 to 3 times greater than when there were no channels. On the native grass, the dye velocities were slower than the computed mean velocities. Dye velocities ranged from less than 3 to almost 5 cm sec^{-1} . The Manning's n computed using these measured flow velocities were 2 times to an order of magnitude greater than previously reported. These values are believed to be more realistic and representative for determining overland flow velocities through vegetation and microchannels around vegetation.

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Table 1. Mean velocity of water and Manning's n across undisturbed soil monoliths of 2 grasses from the Central Plains Experimental Range in a laboratory flume.

Grass Species	Slope Flume	Slope Surface	Reps	Flow Rate	Flow Depth	Velocity Mean	Velocity Dye	Manning's n Mean	Manning's n Dye
	----(%)------		(No.)	($cm^3 sec^{-1}$)	(cm)	---($cm\ sec^{-1}$)---			
Blue grama	3.4	3.9	6	20	1.8	4.3	3.1	.341	.406
		3.9	6	30	2.1	5.1	3.8	.316	.369
Inland salt grass	3.4	4.3	4	21	1.5	3.9	2.6	.896	.534
		4.3	4	30	1.8	4.2	3.1	.703	.465
Blue grama	7.0	7.0	2	20	1.0	11.6	1.9	.074	.475
		5.8	4	30	1.5	8.2	3.8	.153	.322
Inland salt grass	7.0	1.5	2	20	0.7	11.6	3.9	.060	.305
		1.5	3	31	1.0	----	4.8	---	.290

Table 2. Velocity of water and Manning's n across an undisturbed blue grama range site on the Central Plains Experimental Range.

Site Designation	Slope	Velocity		Manning's n	
		Advancing Front	Dye	Advancing Front	Dye
	(%)	---------(cm sec^{-1})--------			
Dry Soil					
A1	8	1.15	3.97	1.142	0.331
A2	5	0.29	1.11	3.579	0.935
A3	7	----	4.39	-----	0.280
B1	6	1.05	3.88	1.083	0.293
B2	6	1.49	3.55	0.763	0.320
B3	8	1.67	4.50	0.786	0.292
B4	8	0.82	4.76	1.601	0.276
Wet Soil					
A1	8	1.65	5.20	0.796	0.252
A2	5	0.49	1.19	2.118	0.872
A3	7	1.75	4.17	0.702	0.294

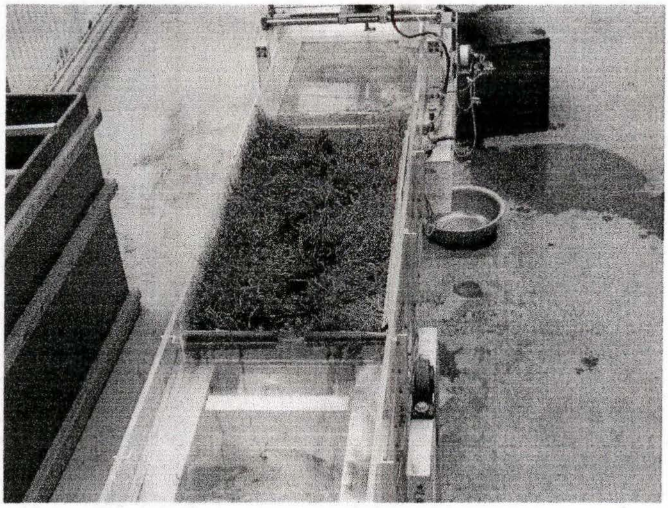


Figure 1. Laboratory photograph of flume for evaluating flow velocities through grass.

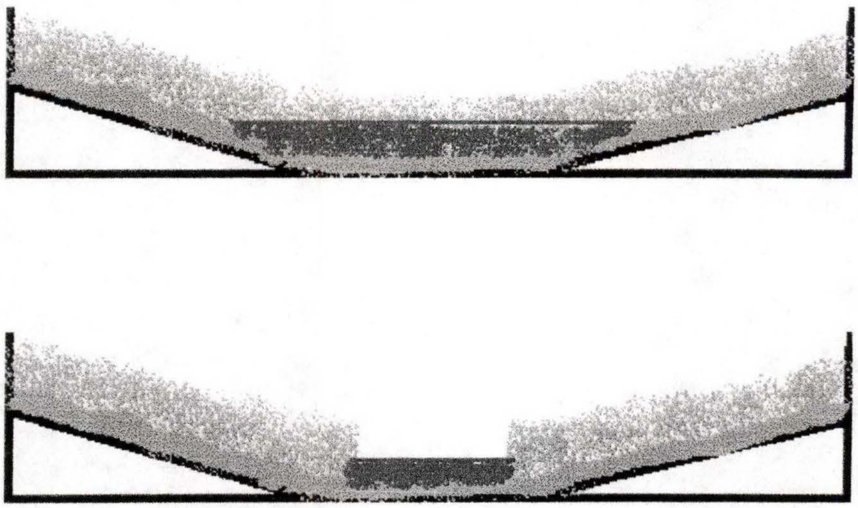


Figure 2. Sketch of flume cross-section of grass matting with and without cut channels.

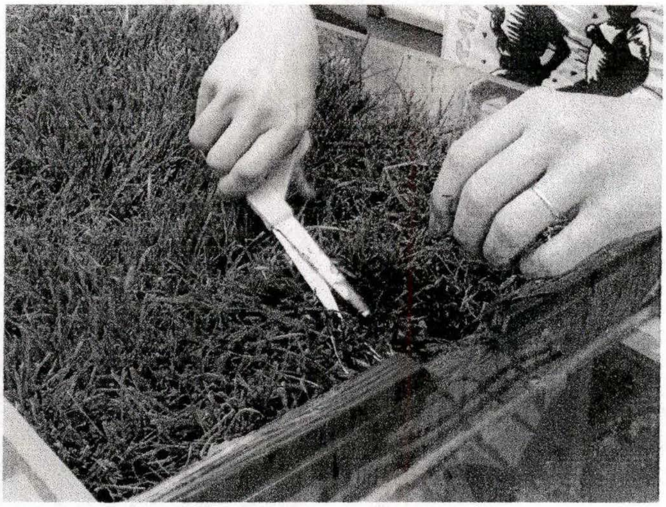


Figure 3. Cutting a flow channel in grass matting.

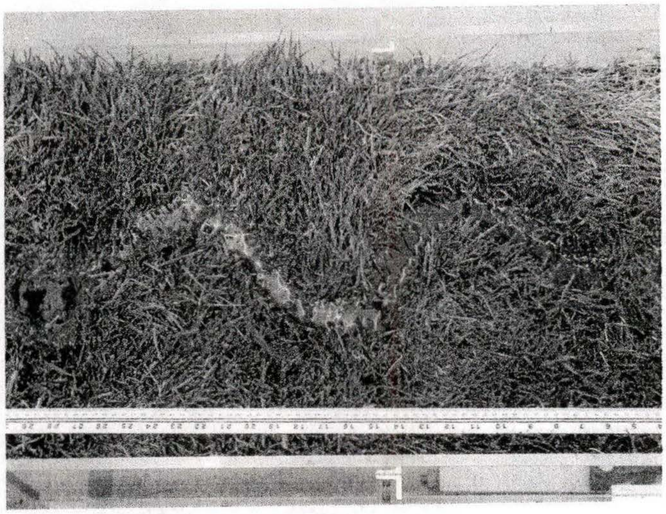


Figure 4. Cut flow path channel in grass matting.

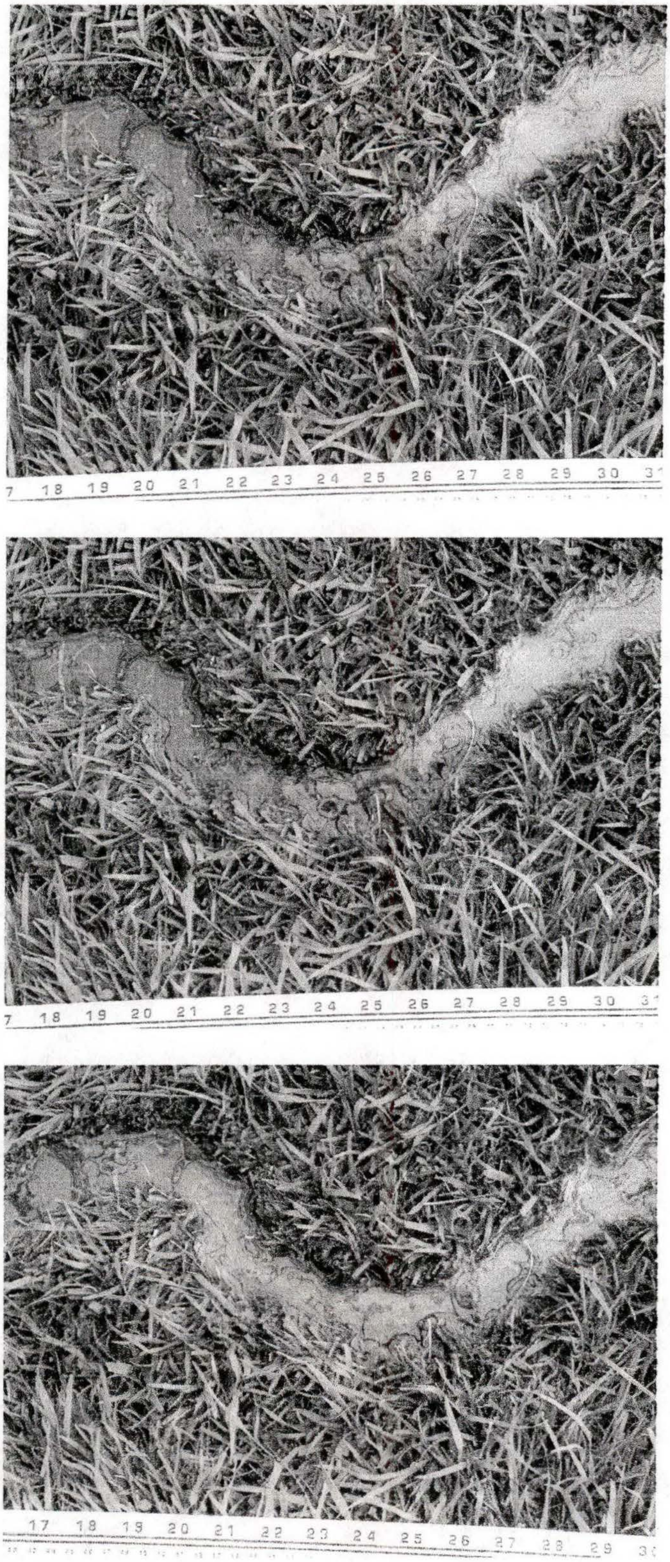


Figure 5. Dye tracer used in flow velocity measurements.

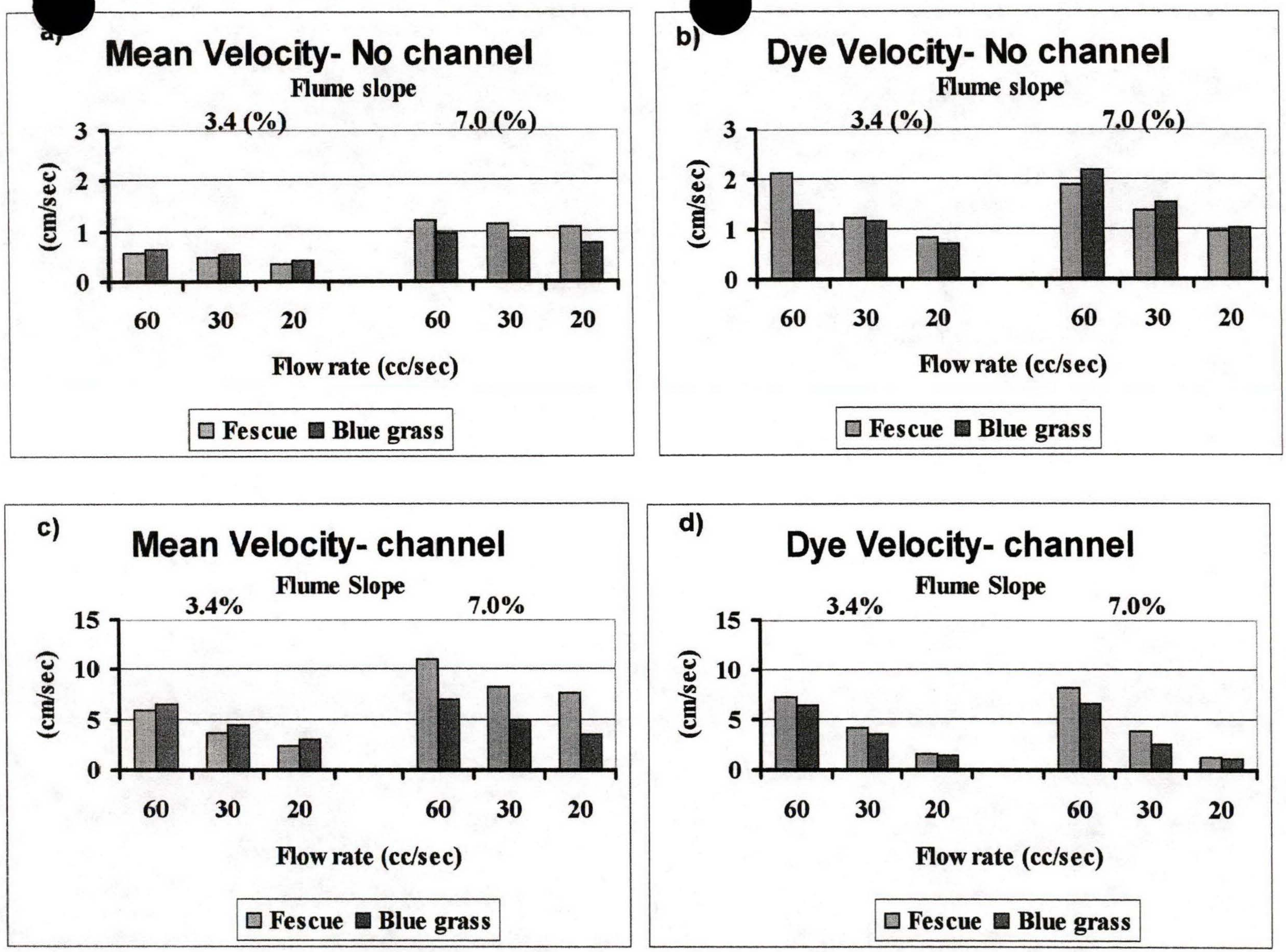


Figure 6. Mean and dye flow velocities in 2 grasses on 2 slopes at 3 flow rates with and without channels cut in grass.

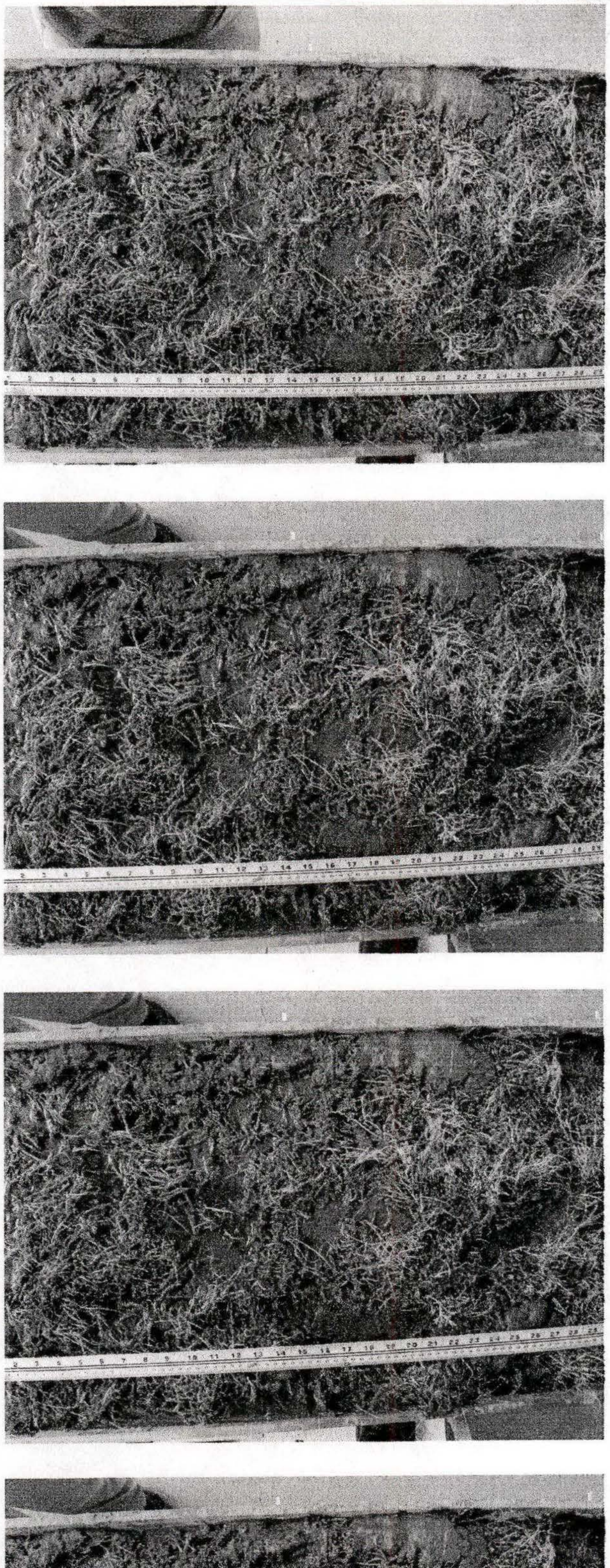
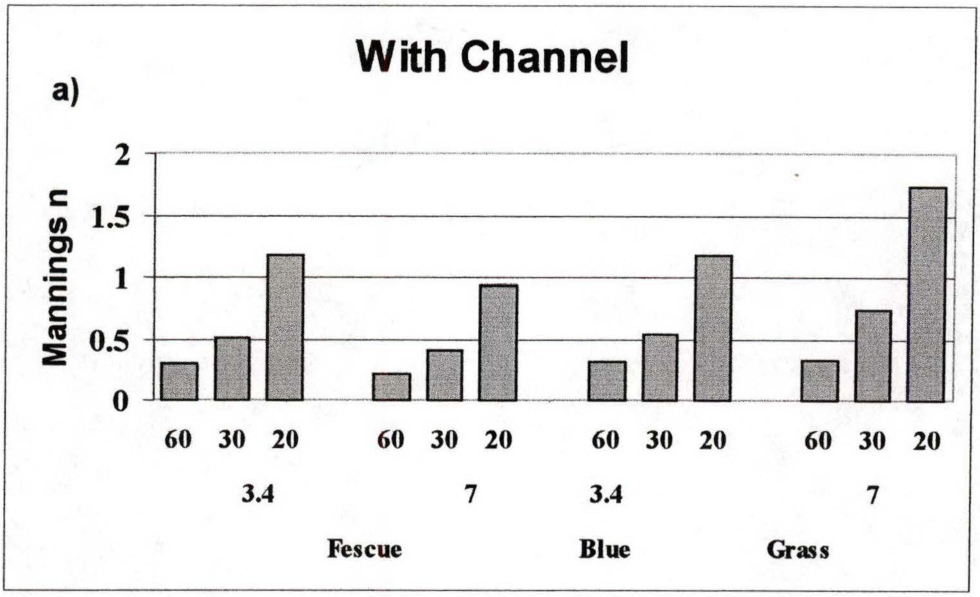


Figure 7. Dye flow across an undisturbed soil monolith of blue grama grass.



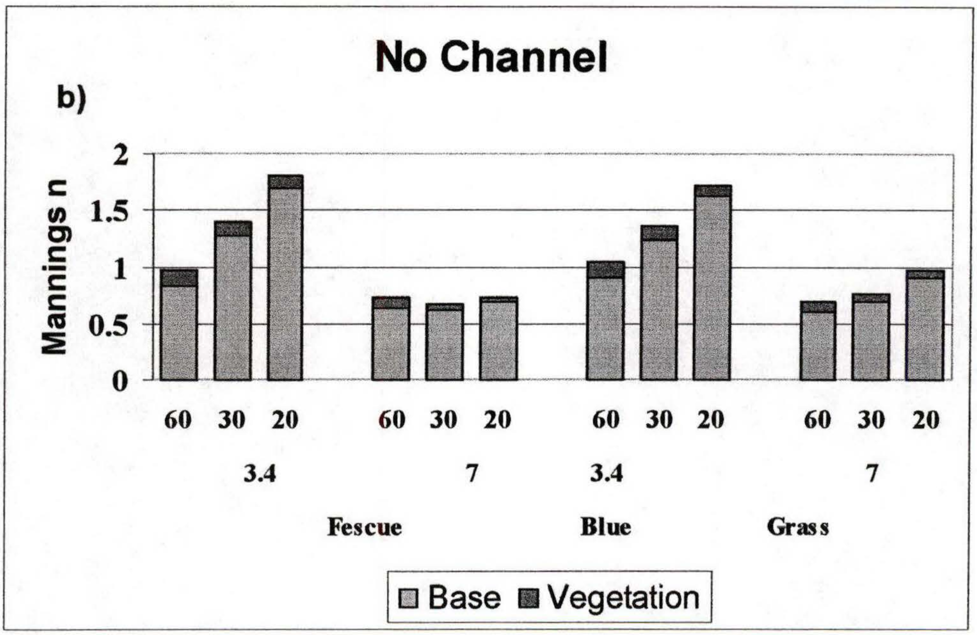


Figure 8. Laboratory determined Manning's n for 3 flow rates and 2 slopes on 2 grasses with and without channels cut in the grass.

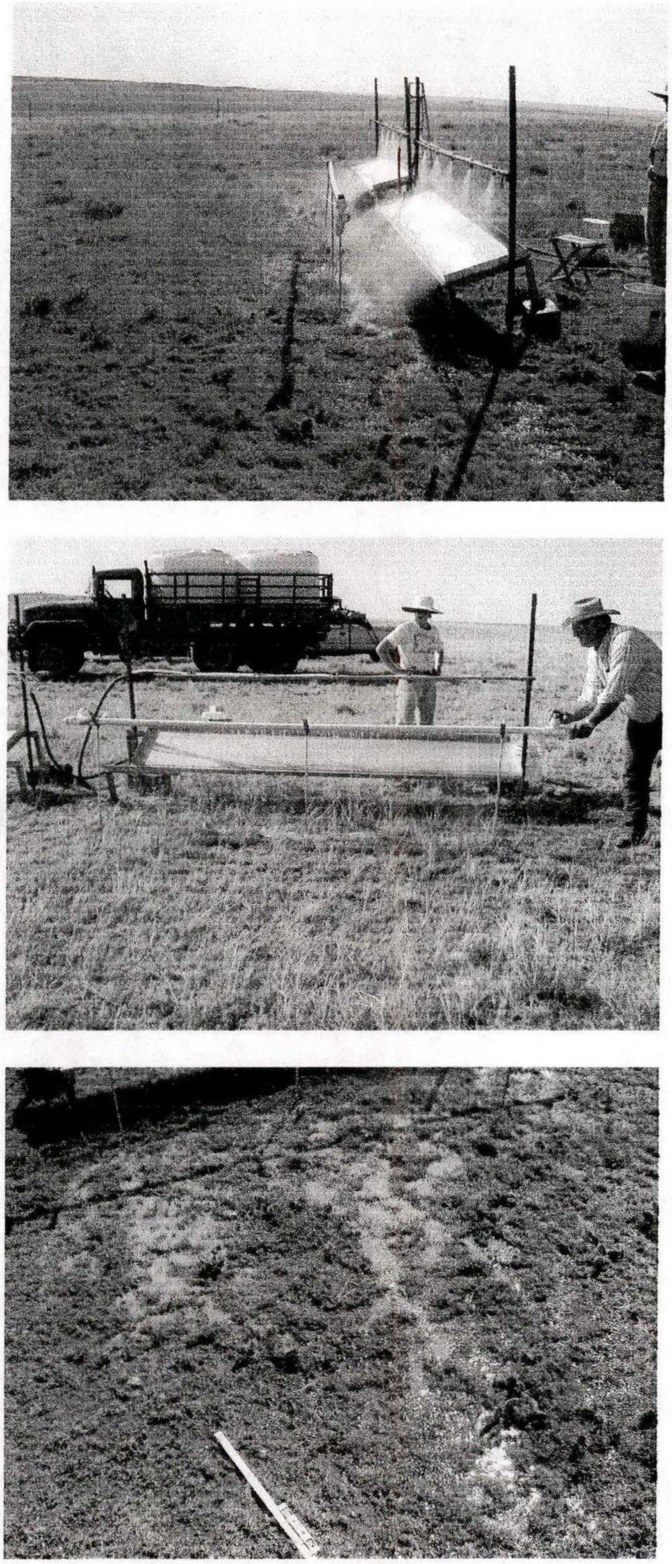


Figure 9. Determining the overland flow velocity at the Central Plains Experimental Range.

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Knowledge to Go Places

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December 23, 2002

MEMORANDUM

TO: Dr. Bruce Rieman

FROM: Wayne Leininger

SUBJECT: Final Report for Joint Venture Agreement #RMRS-99605-RJVA

Enclosed are 3 copies of the final report for the Joint Venture Agreement that I have with the Rocky Mountain Station. The project verified concerns that hydrologists have had for some time that assumptions used in runoff models are not correct. Gary Frasier and I hope to get this manuscript published this coming year to help correct this assumption. Thank you for your support in getting this project completed.

If you have any questions, please contact me.

Have a Merry Christmas and Happy New Year!

cc. Sponsored Programs

" Final Report"

RMRS Library

United States Department of Agriculture	**Forest Service**	**Rocky Mountain Research Station**	**316 E. Myrtle Boise, Idaho 83702**

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Research Fishery Biologist

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January 2, 2003

To: Grants and Agreements

Re: Agreement RMRS-99605-RJVA, "Overland Flow in Microchannels on Rangeland".

We have received a satisfactory final report for this project. The report should complete all obligations for the cooperator.

Sincerely,